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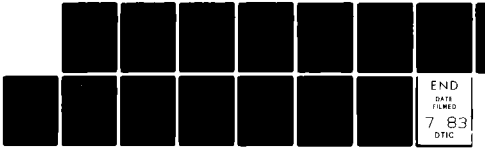

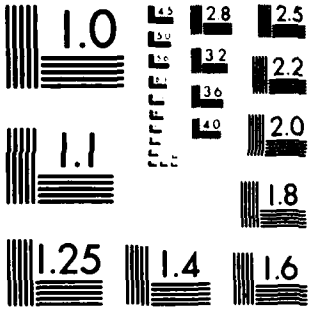

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We present an overview of the technique of pulsed opto-acoustics, whereby an excitation beam of short pulse-duration and low duty cycle is used to generate acoustic transients which can be detected by contact as well as non-contact acoustic detection techniques. Theories of pulsed opto-acoustic generation depending on the source dimensions for the simple case of weak optical absorptions are discussed. Various methods of acoustic detection involving piezoelectric ceramics, thin films, or optical beams are reviewed. (Continued on reverse side)

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Pulsed Opto-Acoustics: Theory and Applications

by

A. C. Tam and H. Coufal

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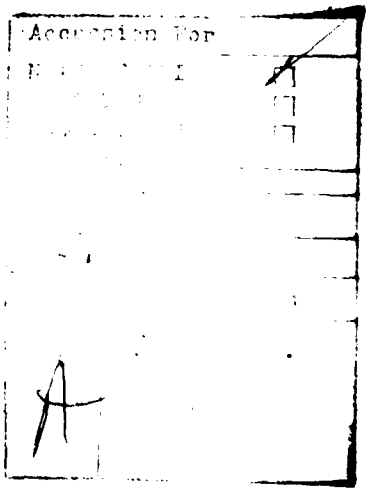

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PULSED OPTO-ACOUSTICS: THEORY AND APPLICATIONS *

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Abstract - We present an overview of the technique of pulsed opto-acoustics, whereby an excitation beam of short pulse-duration and low duty cycle is used to generate acoustic transients which can be detected by contact as well as non-contact acoustic detection techniques. Theories of pulsed opto-acoustic generation depending on the source dimensions for the simple case of weak optical absorptions are discussed. Various methods of acoustic detection involving piezoelectric ceramics, thin films, or optical probe beams are reviewed. Applications discussed include monitoring weak absorptions in highly transparent materials or in trace detection, acoustic material testing utilizing either contact or non-contact detection methods, and the generation of very high pressure transients.

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PULSED OPTO-ACOUSTICS: THEORY AND APPLICATIONS

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Résumé - Nous présentons une revue des techniques de génération et détection d'impulsions opto-acoustiques, où un faisceau d'excitation de trés courte devée et de basse fréquence de répétition est utilisé pour générer des phénomènes acoustiques transitoires pouvant étre mis en évidence par des techniques de détection acoustique impliquant un contact direct aussi bien que celles évitant le contact auee l'échantillon. Sont discutées aussi les théories de génération d'impulsions opto-acoustiques dépendant des dimensions de la source pour le simple cas de faibles absorptions optiques. Différentes méthodes de détections acoustiques utilisant des céramiques piézoélectriques, des films minces, ou des méthodes optiques, sont passées en revue. Les applications discutées incluent la mesure de faibles absorptions dans des mat'eriaux fortement transparents ou des détections en trace, contrôle de matériaux par détection d'impulsions acoustiques soit par contact ou non-contact et la génération de phénomènes transitoires de très haute pression.

Abstract - We present an overview of the technique of pulsed opto-acoustics, whereby an excitation beam of short pulse-duration and low duty cycle is used to generate acoustic transients which can be detected by contact as well as non-contact acoustic detection techniques. Theories of pulsed opto-acoustic generation depending on the source dimensions for the simple case of weak optical absorptions are discussed. Various methods of acoustic detection involving piezoelectric ceramics, thin films, or optical probe beams are reviewed. Applications discussed include monitoring weak absorptions in highly transparent materials or in trace detection, acoustic material testing utilizing either contact or non-contact detection methods, and the generation of very high pressure transients.

INTRODUCTION

There are two commonly used opto-acoustic (OA) techniques: a continuum wave (CW) modulated technique /1/ whereby the excitation beam is modulated near 50% duty cycle, and the acoustic signal generated inside the sample or in an adjacent fluid is detected usually by a lock-in amplifier, a correlator or a Fourier analyser; and a pulsed technique /2/ whereby the excitation beam is modulated at very low duty cycle (*e.g.*, $\lesssim 10^{-5}$) but with high peak intensity of short duration, and the acoustic signal is detected usually by a box-car averager or a transient digitizer. In the CW case the signal is typically analysed in the frequency domain; amplitude and phase of one or several Fourier components are measured and filters can be used to suppress noise. In the pulsed technique, however, the signal is acquired and analysed in the time domain making simple gating techniques for noise suppression possible. Of course, pulsed excitation can be regarded as frequency-multiplexed probing with many Fourier components at the same time. The features of the two OA techniques are indicated in Fig. 1. If the same average optical power is used on a weakly absorbing sample, we have found experimentally that the pulsed technique gives typically much higher detection sensitivity compared to the CW modulated technique. This can be qualitatively understood as follows. For the CW modulated case, the OA signal is present continuously, while in the pulsed case, the OA signal is "compressed" into a large-amplitude signal within a short period

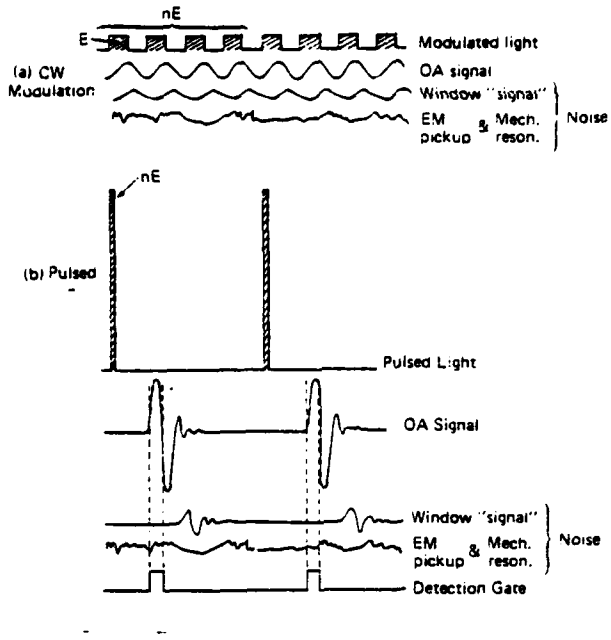

Figure 1. Schematic comparison of the CW modulated opto-acoustic method and (b) the pulsed opto-acoustic method.

with a well-defined delay time from the excitation pulse. Hence, in the latter case, a detection gate can be used so that the detection electronics only accept signals within the gate period. This allows discrimination against any window "signals" and "echos" which have a different delay time, and any signals due to light-scattering onto the transducer with a delay time approaching zero. Also, any noise due to electro-magnetic pick-up can be more easily suppressed in the pulsed detection mode, and acoustic noise is negligible on short detection time scales. The above idea of high sensitivity detection using pulsed excitation and gated detection has already been used in other fields of physics, for example, in single-atom detection /3/. A qualitative comparison of CW modulated techniques *versus* pulsed technique is given in Table I.

Table I. Comparison of CW Modulated and Pulsed OA Techniques

	CW Modulated	Pulsed
Acoustic energy conversion efficiency	Low	High
Thermal diffusion (3-D effects)	may be important	usually negligible
Boundary effects	important	unimportant
Unmodulated background heating	usually substantial	usually small

This paper is mainly concerned with the pulsed OA technique and those applications where the pulsed technique is more advantageous than the CW modulated technique. However, we must

point out that there are other situations where CW modulated technique may be more advantageous, (3)
e.g., for strongly absorbing materials or materials that can be damaged by intense pulsed excitation, and in cases where well-defined modulation frequencies are needed to have defined thermal diffusion lengths (*e.g.*, for depth-profiling applications).

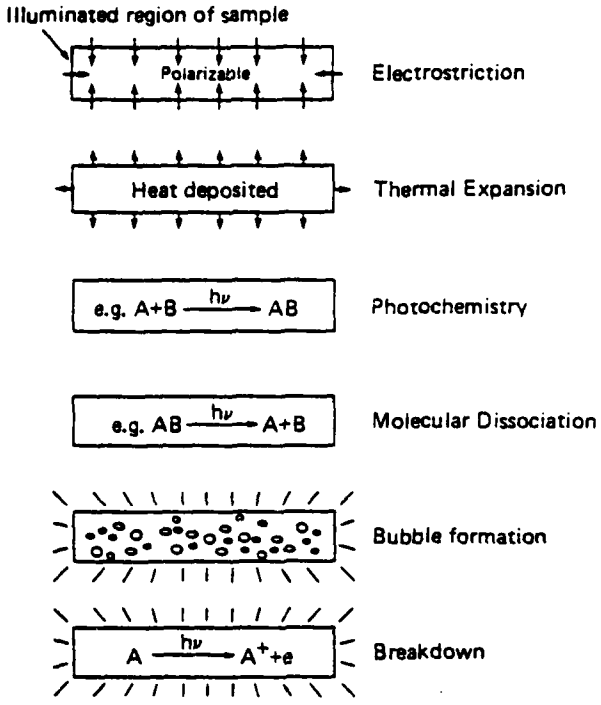

Figure 2. Some common mechanisms for opto-acoustic generation. Efficiency usually increases downwards.

THEORY

OA generation can be due to diversified processes. Some of the possible OA generation mechanisms are shown in Fig. 2, where the OA generation efficiency η (*i.e.*, acoustic energy generated/light energy absorbed) generally increases downward for the mechanisms listed. For electrostriction or thermal expansion mechanisms, η is small, typically on the order of 10^{-12} to 10^{-8}, while for breakdown mechanisms, η can be as large as 30% /4/. We will limit our present discussion to the cases where η is small.

Semi-Quantitative Theory for Small Laser Radius R_s

We will discuss a simplified case of OA pulsed generation with pulses short enough to neglect thermal diffusion (this usually means light pulses shorter than one millisecond). Consider a long cylindrical source with small radius R_s (see Fig. 3a), *i.e.*, $R_s < c\tau_L$ where c is the sound velocity in the medium and τ_L is the laser pulse width. The initial expansion ΔR_s of the source radius R_s immediately after the laser pulse is given by

$$\pi(R_s + \Delta R_s)^2 \ell - \pi R_s^2 \ell = \beta V \Delta T \tag{1}$$

with the initial temperature rise

$$\Delta T = \frac{E\alpha\ell}{\rho V C_p} \tag{2}$$

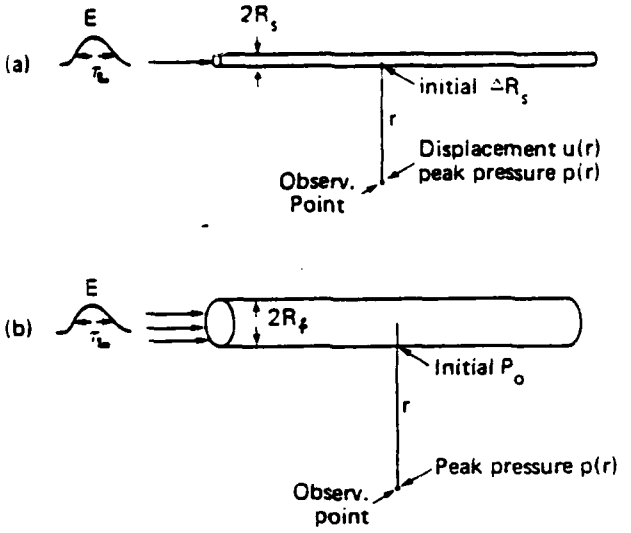

Figure 3. Pulsed OA generation for weak absorption in infinite medium for (a) laser beam radius R_s being smaller than $c\tau_L$ and (b) laser beam radius R_f being larger than $c\tau_L$.

where ℓ is the length of the OA source (assumed long), β is the expansion coefficient, $V = \pi R_s^2 \ell$ is the source volume, E is the laser pulse energy, α is the absorption length (with $\alpha L << 1$), ρ is the density and C_p is the specific heat at constant pressure. Combining Eqs. (1) and (2) and assuming $\Delta R_s << R_s$ (true in all cases we are considering), we have

$$\Delta R_s = \frac{\beta E \alpha}{2\pi R_s \rho C_p} \qquad (3)$$

which has been given, for example. by Patel and Tam /2/. The peak displacement $U_s(r)$ at the observation point at distance r from the OA source (for $r_s << \ell$) varies as $r^{-1/2}$ because of conservation of acoustic energy, as described by Landau and Lifshitz /5/ for a cylindrical acoustic wave:

$$U_s(r) = \Delta R_s (R_s/r)^{1/2} = \frac{\beta E \alpha}{2\pi R_s^{1/2} \rho C_p r^{1/2}} . \qquad (4)$$

The peak acoustic pressure $P_s(r)$ at position r is related to the acoustic displacement $U_s(r)$ by

$$P_s(r) \approx c\rho U_s(r)/\tau_L . \qquad (5)$$

Substituting Eq. (4) into (5), we obtain the peak OA pressure observed at r for small source radius as

$$P_s(r) \approx \frac{\beta c E \alpha}{2\pi R_s^{1/2} C_p \tau r^{1/2}} . \qquad (6)$$

Semi-Qualitative Theory for Fat Laser Radius R_f

The opposite case of a fat laser radius, *i.e.*, $R_f > c\tau_L$ (see Fig. 3b) is also simple. Here, a large radius means that the heated value does not have time to expand isobarically immediately after the laser pulse; instead a pressure increase P_0 is produced at the cylinder surface immediately after the laser pulse is absorbed, as given by

$$P_0 = \rho c^2 \beta \Delta T = \frac{\rho c^2 \beta E \alpha}{\pi R_f^2 \rho C_p} \tag{7}$$

where ρc^2 is the bulk modulus of the medium and Eq. (7) is obtained from the consideration that the stress P_0 and the strain $\beta\Delta T$ is related by the bulk modulus. Again, the peak acoustic pressure $P_f(r)$ for the cylindrical wave scales as $r^{-1/2}$, so that

$$P_f(r) = P_0(R_f/r)^{1/2} = \frac{\beta c^2 E \alpha}{\pi R_f^{3/2} C_p r^{1/2}} . \tag{8}$$

Comparison of the Small or Fat Cases

Comparing Eqs. (6) and (8), we see that

$$\frac{P_f(r)}{P_s(r)} \approx \left(\frac{R_s}{R_f}\right)^{1/2} \left(\frac{c\tau_L}{R_f}\right) < 1 \tag{9}$$

which shows that a fat source radius produces a weaker OA pulse compared to a small source radius, with all other conditions being identical. This is intuitively appealing, since for the fat rac case ($R_f > c\tau_L$), the contributions from different positions in the source do not add up coherently ause of the long acoustic transit time across the diameter.

Both Eqs. (6) and (8) imply that the peak acoustic pressure P is linearly dependent ne laser pulse energy E, which means that the acoustic energy E_{ac} varies as E^2. Hence, the OA generation efficiency η is

$$\eta = \frac{E_{ac}}{E} \propto E . \tag{10}$$

Thus higher OA efficiency occurs for higher laser energy, and this is true for all cases of OA generation by a thermal expansion mechanism.

Rigorous Theory of OA Generation by Thermal Expansion and Electrostriction

Rigorous theories of OA generation by thermal expansion mechanisms have been given by White /6/, Gourney /7/, Hu /8/, Liu /9/ and others. Rigorous theories of OA generation by thermal expansion and by electrostriction have been given by Lai and Young /10/. Here, we indicate the essence of Lai and Young's theory for the weak absorption case. The basic equations of the OA generation are the equation of motion:

$$\rho \ddot{\vec{u}} = -\nabla p \tag{11}$$

and the equation of expansion:

$$\nabla . \vec{u} = -\frac{p}{\rho c^2} + \beta T - \frac{\gamma I}{2 n c_L \rho c^2} \tag{12}$$

where $\vec{u}(r,t)$ is the acoustic displacement at distance r from the axis of the OA cylindrical source, p(r,t) is the acoustic pressure, T is the temperature rise due to the laser pulse of an intensity I(r,t), γ is the electrostrictive coefficient, n is the refractive index of light and c_L is the velocity of light in vacuum. We use the notation that one or two dots above a quantity indicates a first or second time derivative. Taking the second time-derivative of Eq. (12), we get

$$\frac{1}{\rho c^2} \frac{\partial^2 p}{\partial t^2} + \nabla . \ddot{\vec{u}} = \beta \ddot{T} - \frac{\gamma}{2 n c_L \rho c^2} \frac{\partial^2 I}{\partial t^2} . \tag{13}$$

Substituting Eq. (11) into Eq. (13) and also using

$$\ddot{T} = \frac{\alpha \dot{I}}{\rho C_p} \tag{14}$$

we get the following inhomogeneous wave equation for the acoustic pressure:

$$\left(\frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \nabla^2\right)p = \left(\frac{\alpha\beta}{C_p}\frac{\partial}{\partial t} - \frac{\rho\gamma}{2nc_L\rho c^2}\frac{\partial^2}{\partial t^2}\right)I \,. \tag{15}$$

A way to simplify the solution of Eq. (15) is possible by introducing /10/ a potential function $\phi(r,t)$ which satisfies the following reduced wave equation:

$$\left(\frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \nabla^2\right)\phi = I(r,t) \,. \tag{16}$$

Equations (15) and (16) imply the following: the acoustic pressure p can be written as the sum of a thermal expansion term p_{th} and an electrostriction term p_{el}, given by

$$p_{th} = \frac{\alpha\beta}{C_p}\frac{\partial\phi}{\partial t} \,, \tag{17}$$

and

$$p_{el} = -\frac{\rho\gamma}{2nc_L\rho c^2}\frac{\partial^2\phi}{\partial t^2} \,, \tag{18}$$

with

$$p = p_{th} + p_{el} \,. \tag{19}$$

Equations (17) and (18) have the following two important implications. First, p_{el} is proportional to the time-derivative of p_{th}, *i.e.*,

$$p_{el} \propto dp_{th}/dt \,. \tag{20}$$

Hence, if p_{th} is at a peak pressure at a time t_1, p_{el} will pass through zero pressure at t_1. Thus, the effect of p_{el} can be minimized by using a boxcar integrator to detect the OA signal with the boxcar gate set at t_1 with a suitable gate width. Secondly, the peak magnitudes $|p_{el}|$ and $|p_{th}|$ are related by:

$$\frac{|p_{el}|}{|p_{th}|} \approx \frac{\rho\gamma C_p}{2nc_L\rho c^2\alpha\beta}\frac{1}{\tau_{OA}} \tag{21}$$

where τ_{OA} is the width of the OA pulse. If we put $\tau_{OA}=1$ μsec, and substitute values for the other parameters in Eq. (21) for typical liquids like water or ethanol, we conclude that

$$\frac{|p_{el}|}{|p_{th}|} \lesssim \frac{10^{-5}\ \mathrm{cm}^{-1}}{\alpha} \,. \tag{22}$$

This means that the electrostrictive pressure is small compared to the thermal expansion pressure, unless α is smaller than $\sim 10^{-5}$ cm^{-1}; however, even in this low absorption case, the electrostrictive pressure effect can be suppressed /10/ (*e.g.*, by a factor of 100) by suitably setting the boxcar gate for detection, as indicated in Eq. (20).

Quantitative solutions of Eqs. (16)-(18) have been obtained by Lai and Young /10/, and some of their results are indicated in Fig. 4.

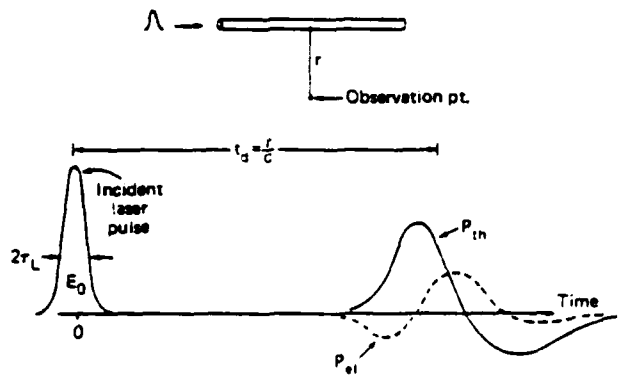

Figure 4. Typical profile of the OA signal due to thermal expansion (p_{th}) and that due to electrostriction (p_{el}) as calculated by Lai and Young (Ref. 10). Only the shapes of p_{th} and p_{el} are indicated; their relative magnitudes are determined by Eq. (21).

DETECTION OF PULSED OA SIGNAL

OA signals generated in condensed matter by pulsed laser sources are typically sharp, with risetimes usually shorter than several μsec. Thus, gas-coupled microphones are not fast enough to detect the true OA signal; furthermore, the serious acoustic impedance mismatch at the gas-sample interface means that very little ($\lesssim 10^{-4}$) of the OA signal in the sample can be transmitted into the gas. Thus, other modes of detection of sharp OA signals are required. Examples include lead zirconate titanate (PZT) or other similar piezoelectric ceramic transducers, thin-film transducers and non-contact "transducers" like laser beam deflection by the acoustic profile.

Piezoelectric Transducers

Many types of piezoelectric ceramics or crystals are commercially available, *e.g.,* PZT, lead metaniobate, lithium niobate, crystalline quartz, *etc.,* and reviews on these transducers are in the literature /11/. For OA detection, the piezoelectric element usually need to have metalized electrodes, and to be mounted in a suitable manner. One way of mounting /12/ is shown in Fig. 5a. Here, a PZT cylinder (PZT 5A from Vernitron, Ohio) of 4 mm diameter and 4 mm height is pressed against a front stainless steel diaphragm that is polished on both sides. The active acoustic sensing element is all enclosed in the stainless steel casing so that the following noise sources are minimized: electromagnetic pick-up, possible corrosion due to contact with reactive samples and absorption of stray light that is scattered towards the transducer. Some other ways of mounting piezoelectric ceramics /13-18/ are indicated in Fig. 5. We see that in some of these other ways, the active element is exposed to the sample directly; while this usually result in a gain in sensitivity (*e.g.,* by a factor of 2), the noise sources mentioned above are not minimized and the signal/noise ratio may not be better at all.

The sensitivity of a PZT transducer (*e.g.,* shown in Fig. 5a) is typically ~ 3 V/atm. This is much smaller than that of a sensitive microphone (*e.g.,* B&K model 4166) with a sensitivity $\sim 5\times10^{3}$ V/atm. However, PZT transducers are preferred (compared to microphones) for pulsed OA studies in condensed matter because of the much faster risetimes and much better acoustic impedance matching for PZT compared to microphones.

Thin Film Polymeric Transducers

Some highly insulating polymeric films can be poled in a strong electric field at elevated temperatures or can be subjected to charged beam bombardment so that they become polarized and exhibit piezoelectric character. Such films include polyvinylidene difluoride (PVF_2), teflon, mylar, *etc.,* with PVF_2 being the most commonly used. There is strong interest in the use of PVF_2 film as

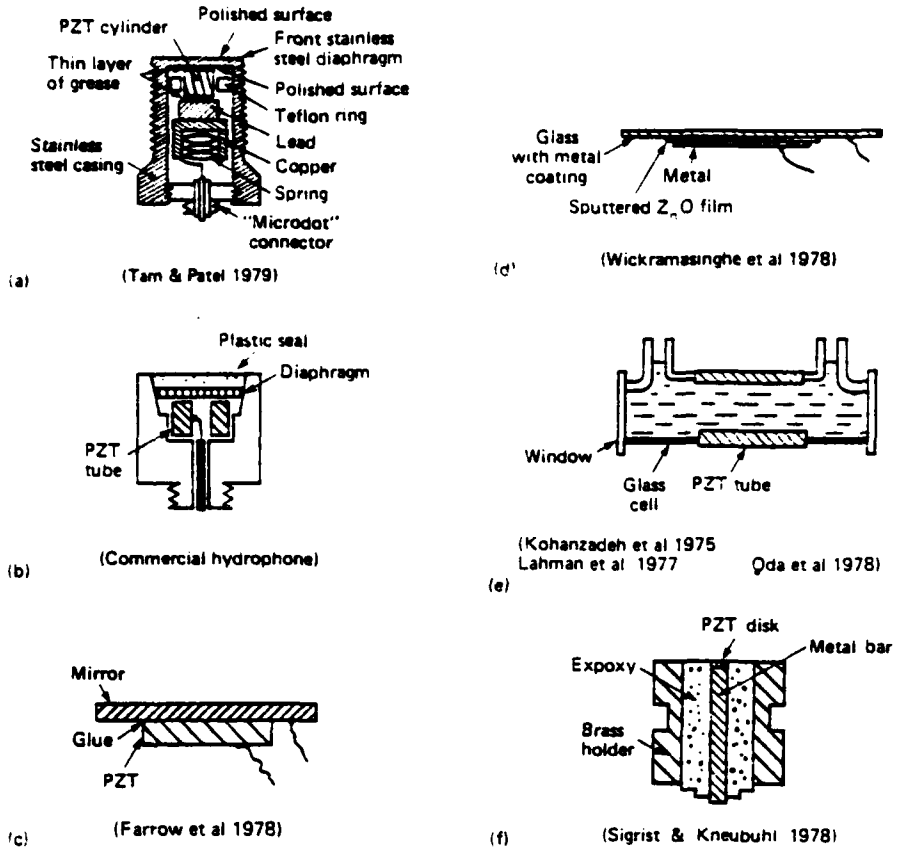

Figure 5. Schematics of some of the methods of mounting PZT or other piezoelectric ceramics or crystals.

transducers for acoustic imaging in the human body because of the non-ringing characteristic of the film (Q is much lower than PZT), fast risetime, flexibility, and good acoustic impedance matching to liquids like water. A disadvantage of PVF_2 is that its sensitivity is typically one order of magnitude lower than PZT. Many ways to mount a PVF_2 film are possible; one way is indicated in Fig. 6. Here, the 4mm×4mm PVF_2 film of 52 μm thickness (Pennwalt, Pennsylvania) with nickel coating on both surfaces as electrodes is glued onto a polished lead backing of thickness ~0.5 mm. The PVF_2 film is spring-loaded onto the sample being studied, with a thin layer of water for acoustic coupling. Tam and Coufal /20/ have shown that such a PVF_2 transducer is capable of ringing-free detection of very fast OA transients (with the acoustic pulse width ~10 nsec) that is excited by a pulsed N_2 laser. An example of a pulsed OA signal observed for an aluminum sample of 2.54 cm thickness excited by an excimer laser (10 ns pulsewidth, 50 mJ pulse energy) detected by the PVF_2 transducer at the end-on position (*i.e.*, epicenter) is shown in Fig. 7, where the first OA pulse arrives after a delay time of 3.959 μs (with respect to the firing of the laser). Multiply-reflected pulses (due to thickness reflections) of similar shape can be clearly observed at intervals of 7.919 μs (with later pulses being weaker than the earlier pulses) for delay times up to ~100 μs. Since the width of the OA pulse is ~10 nsec wide (Fig. 7) and the peak position can be located to an accuracy of ~1 nsec, we see that the observation of multiply-reflected signals at late delay times (~100 μs) permits an accuracy of acoustic velocity determination of ~1 nsec/100 μsec=10^{-5}. Also, ultrasonic attenuation and dispersion can be measured. This clearly indicates the usefulness of short pulsed OA generation with fast ringing-free detection for new material testing applications.

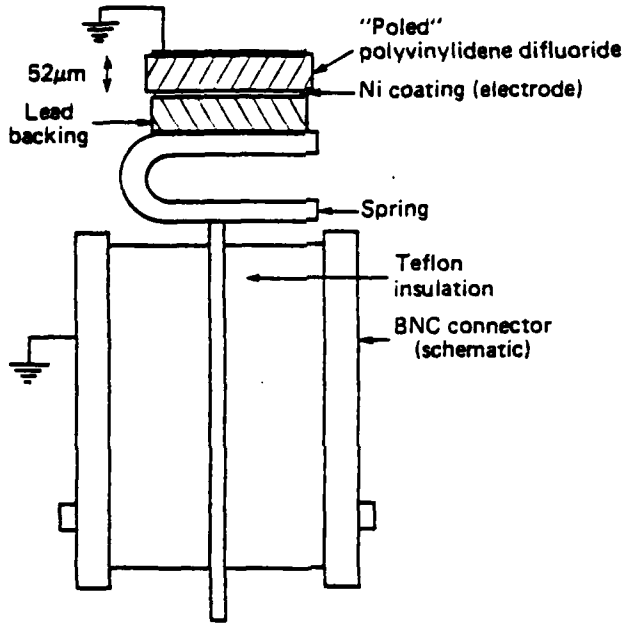

Figure 6. Schematic diagram of a method to mount a polyvinylidene difluoroide foil for OA detection (not to scale).

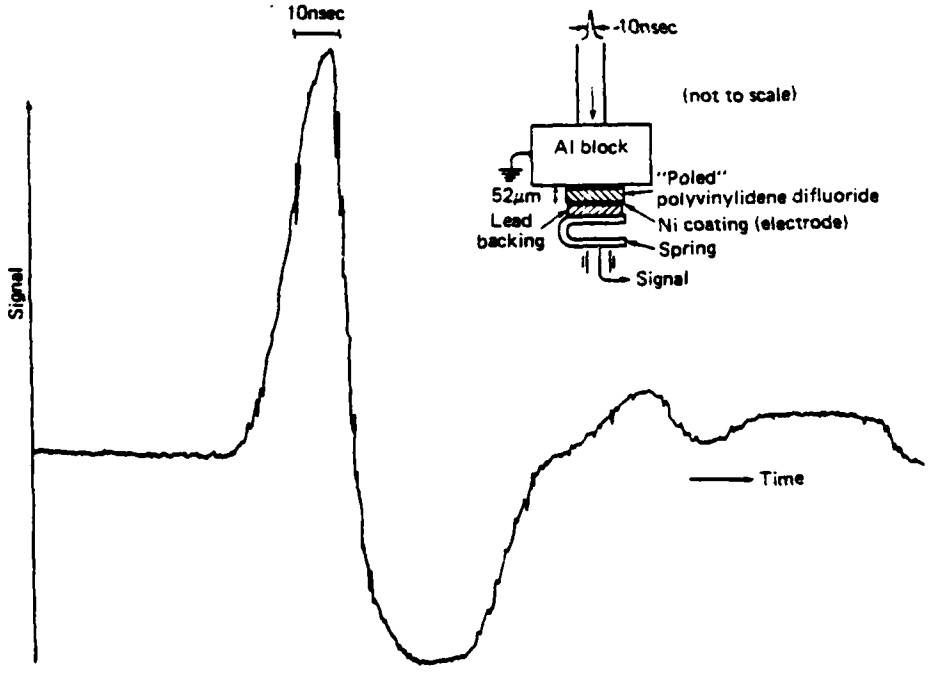

Figure 7. Observed pulsed OA signal in an aluminum sample 2.54 cm thick excited by an unfocused pulsed excimer laser of ~50 mJ energy and 10 nsec duration.

Other Pulsed OA Transducers

Other types of transducers for detecting pulsed acoustic signal have been described in the literature. For example, Dewhurst and co-workers /21,22/ have used capacitance transducers for detection of OA pulses generated in metallic samples by pulsed Nd:YAG lasers. Amer and co-workers /23/ have used a continuum probe laser beam directed at the sample surface to detect the surface distortions due to the thermal or acoustic effects excited by a pulsed laser. Tam *et al.* have used a continuous probe laser beam to detect the transient refractive index profile of the OA pulse in gases /24/ as well as in liquids /25/; such acoustic refractive index profile causes the probe beam to undergo a transient deflection proportional to the spatial derivative of the refractive index.

The above are examples of detection of the acoustic profile generated by the pulsed heating by the excitation beam. Of course, the pulse heating also generates a temperature gradient (close to the excitation beam), which dissipates slowly by thermal diffusion. Many methods to detect this pulsed photo-thermal heating are possible; we can mention only several examples. The refractive index profile associated with this diffusive thermal gradient can be probed by various methods, including thermal lensing /26/, probe-beam deflection /27/ and "mirage" detection with gas coupling /28/. The thermal gradient also affects the Boltzmann distribution of the molecular states in a gas, detectable by absorption spectroscopy /29/; this can be called a Boltzmann spectroscopy method for detecting the photo-thermal effect. The pulsed heating of a condensed sample causes a transient increase of the thermal radiation (or "grey" body radiation), which can be detected /30/ by a suitable infrared detector like HgCdTe; this pulsed photo-thermal radiometric technique (which is an extension of earlier CW modulated photo-thermal radiometry /31/) can be quite useful for single-ended remote sensing applications.

APPLICATIONS OF PULSED OA METHODS

The features of the pulsed OA generation processes include (1) large signals can be generated and excellent discrimination against noise (due to window absorption and scattered light) can be achieved; (2) short and well-characterized acoustic transients can be produced; (3) very high pressure transients can be produced. Applications based on these features are listed below.

Weak Absorptions

Intense laser pulses of short duration and low repetition rates can be advantageously used to obtain detectable OA signals in cases of weak absorption. In this way, linear absorption spectroscopy of small absorption features in liquids /2/ and in solids /32/ have been detected. Furthermore, the high peak power of the excitation radiation means that non-linear optical absorption like multiphoton absorptions /33,34/ or stimulated Raman scattering /35,36/ in gases as well as in condensed matter can be observed. These higher order optical absorption processes are readily observable with the pulsed OA detection scheme, but not with CW modulated OA methods. Also, kinetic studies with a time resolution in the order of ns can be conducted readily with pulsed techniques but not with CW methods. A review of pulsed OA techniques for weak-absorption spectroscopy has been given by Patel and Tam /2/.

Material Testing and Optical Ultrasonics

Using very short duration lasers pulses, sharp and well-defined acoustic pulses of duration 10 ns or shorter can be produced. Together with fast ringing free transducers /20/ new approaches to material testing are viable /37/. Ultrasonic velocities in materials for example can be obtained by timing the OA pulse propagation, and accuracies ~10^{-4} or better can usually be attainable with a path length of several cm. Also, ultrasonic attenuation or dispersion is obtained by observation the OA pulse magnitude or shape as a function of path length. Dewhurst and coworkers /21,22/ have made a series of quantitative studies to characterize the OA pulses in solids generated by Nd:YAG laser pulses. Tam and Coufal /20/ have shown that OA pulses of ~10 ns width can be

produced in solid samples by laser pulses of 1 mJ energy: they showed that such OA pulses not only can provide longitudinal and shear wave velocities, but also can be used for ultrasonic imaging applications. In a round or elliptical geometry, sound waves generated at one focal point are refocused after reflection from the perimeter /38/. Analysis of these echos renders information on the symmetry of the sample, with asymmetry of a supposedly symmetric sample frequently being indicative of a defect. Imaino and Tam /39/ have used OA pulse generation to study the acoustic properties of powders; here, acoustic generation using transducers is difficult because of the poor coupling of sound from the transducer into a powder sample.

In the above examples of material testing, a transducer contacting or near the sample is needed. However, material testing without such a transducer is also possible; an optical probe beam can be used to detect the OA pulse, as mentioned in Sec. 3.3. We shall use the name "optical ultrasonics" to indicate such non-contact methods of ultrasonic testing, where only optical beams are used to perform otherwise conventional ultrasonic measurements. Such optical ultrasonic applications include the measurement of sound velocity and detection of shock waves in hot corrosive gases /24/, the measurement of temperature-dependent sound velocities in corrosive liquids /25/ and the simultaneous measurement of temperature and flow velocities in flowing fluids /40/. Obviously, optical ultrasonics is especially advantageous for inaccessible samples (*e.g.*, inside a vacuum chamber) or for highly hostile environment (*e.g.*, in electrical plasmas or in combustions /41/).

High Pressure Generation

With focused pulsed laser excitation, very large acoustic transients can be produced via boiling or dielectric breakdown. Askaryan *et al.* /42/ were the first to observe boiling or effervescence due to pulsed lasers in liquids. Teslenko /4/ has estimated that a OA generation efficiency of ~30% is possible in pulsed laser-induced breakdown. Thus, very short and intense laser pulses can provide transient pressure amplitudes of many MBar, which can otherwise be obtained only by strong explosions. Thus, pulsed OA generation can be quite useful for high-pressure scientific investigation.

It should be pointed out that the laser energy need not be large to produce high pressures, since the excitation volume can be quite small. For example, if a short-pulsed laser is focused to a 1 μm diameter spot at the surface of a highly opaque aqueous solution with an optical absorption length of ~1 μm, boiling in the irradiated volume can be produced by a laser energy of ~2 nJ, and a large OA pulse or shock wave can be produced. This is believed to be the mechanism of the effect of "Photoacoustic Ejection from a Nozzle" (*i.e.*, PEN) observed by Tam and Gill /43/; they showed that a laser pulse of ~1 μJ energy and 1 μsec duration focused onto an ink reservoir connected to a 2 μm nozzle can reproducibly cause an ink droplet to be ejected from the nozzle. Thus, PEN should be useful for printing applications.

CONCLUSIONS

In this paper, we have attempted to present an overview of the theory and applications of pulsed OA techniques. The theories for the simple case of weak absorption are given, and the difference between small and large optical beam radius is discussed. Various detectors (contact and non-contact) of the OA pulse are described. Examples of applications where pulsed OA methods are advantageous (rather than CW modulated OA techniques) are given. This paper is far from being exhaustive. We hope, however, that the important features of the pulsed OA technique have been discussed.

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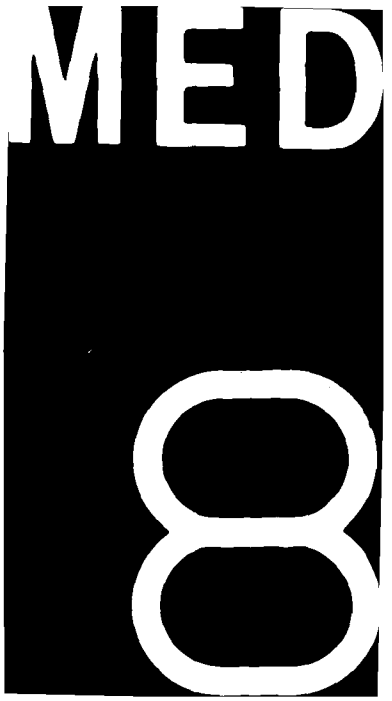
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